

# Potential High Efficiency Solar Cells—Applications from Space Photovoltaic Research

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POTENTIAL HIGH EFFICIENCY SOLAR CELLS - APPLICATIONS FROM  
SPACE PHOTOVOLTAIC RESEARCH

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SUMMARY

NASA involvement in photovoltaic energy conversion research development and applications spans over two decades of continuous progress. Solar cell research and development programs conducted by the Lewis Research Center's Photovoltaic Branch have produced a sound technology base not only for the space program, but for terrestrial applications as well. The fundamental goals which have guided the NASA photovoltaic program are to improve the efficiency and lifetime, and to reduce the mass and cost of photovoltaic energy conversion devices and arrays for use in space. The major efforts in the current Lewis program are on high efficiency, single crystal GaAs planar and concentrator cells, radiation hard InP cells, and superlattice solar cells. A brief historical perspective of accomplishments in high efficiency space solar cells will be given, and current work in all of the above categories will be described. The applicability of space cell research and technology to terrestrial photovoltaics will be discussed.

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INTRODUCTION

The magnitude of NASA's photovoltaic space activities have not been large. With the exception of the Skylab launch in 1973, most NASA missions have been at the 2 or 3 kW level or below. Future NASA missions may be an entirely different story, however. As shown in Figure 1, the desire for more sophisticated, longer-lived missions will push power requirements up an order of magnitude and more. A low-earth manned space station, for example, might require up to 125 kW of power in the station itself. This would in turn require a solar array output capacity in excess of 300 kW, and would represent almost three times the power generating capacity that NASA has launched in the past 20 years. Such an array will be the dominant physical feature on the space station, and emphasizes the need to reduce the area, weight, and cost of large space arrays. Future power requirements for geosynchronous applications are also expected to rise in the coming decade, although few such missions will be solely NASA's. The primary uses of GEO spacecraft will be for commercial and military communications networks. In these applications in particular, a premium is placed on higher efficiency, lighter weight, and longer life. Cell and array cost is important, but is not as important a driver as it is for large LEO arrays. A key figure of merit for GEO arrays is the ratio of output power to total array mass in watts per kilogram. NASA's most recent GEO satellite, TDRSS (Tracking Data Relay Satellite System), had an approximate beginning-of-life (BOL) specific power of 35 W/kg, and a BOL array output of about 2 kW. Future communication satellite power requirements are expected to range from 5 to 10 times that level. Moreover, volume and weight constraints of current and proposed GEO launch vehicles make it desirable to increase both efficiency and

specific power significantly beyond present levels. End-of-life specific powers approaching 250 W/kg may well be needed to meet such constraints. The payoff will be measured directly in terms of increases in the active payload of the satellite. The whole question of BOL and EOL power levels brings up one of the major differences between desirable cell attributes for space use versus terrestrial applications. The largest contributing factor to reduced power output over time in space, barring some sort of mechanical failure on the array, is cell degradation caused by the natural radiation environment that a satellite encounters. A typical GEO communications satellite array will be oversized at BOL by up to 40 percent to assure that it will have sufficient power to operate for at least 7 years. As a result, any potential high efficiency solar cell intended for space application must also be capable of demonstrating high tolerance to radiation. The long term NASA goal is to demonstrate less than 1 percent loss in BOL power in space cells over a period of 10 years. To do so requires that we understand the fundamental efficiency-degrading mechanisms of space radiation, and find ways to overcome them.

It is important to mention at this point one other obvious difference between space and terrestrial cell research: the difference in the spectral intensities of solar insolation in the two environments. Figure 2 shows a plot of spectral intensity as a function of wavelength for the air mass zero (AM0) outer space spectrum, and the air mass 1.5 (AM1) terrestrial spectrum (ref. 1). The major difference between them is the increased amount of energy available at the shorter wavelengths in space - a wavelength region that has typically been difficult to convert to electricity efficiently. As a result, cell efficiencies quoted for terrestrial application are higher than their equivalent space values by as much as 25 percent. A 17 percent AM1 efficient cell will typically be less than 14 percent efficient at AM0. Much of the emphasis in device research for space cells centers on improving their so-called blue response, and has made it important for researchers in the field to understand surface as well as bulk phenomena in semiconductor physics. It is now generally accepted, e.g., that the next major efficiency gains in space-qualified solar cells will require understanding and control of the effects of surface and interface electronic states to achieve higher blue response and longer photogenerated minority carrier lifetimes in those devices.

#### SILICON SPACE SOLAR CELLS

The silicon solar cell has been relied on almost exclusively for photovoltaic power generation in space since the inception of the space program. Figure 3 shows the evolution of efficiency in space silicon solar cells since approximately 1970. Essentially all cells flown prior to that time were made from 10-ohm-cm material, and had AM0 efficiencies on the order of 10 percent. Work in the early seventies resulted in the violet cell (ref. 2) with an efficiency in excess of 14 percent, but it quickly became apparent that higher efficiencies could not be achieved without lowering the resistivity of the starting material (i.e., using more heavily doped n-type silicon). Since the short-circuit current of the cells at that time was very close to the optimum expected, it also became evident that the key to higher efficiency was to increase the open circuit voltage to the 700 mV range. Despite a considerable effort to develop the cell, it still has not reached its full potential. The major barrier that has to be overcome before silicon cells will perform as predicted is the reduction of unwanted recombination of photogenerated carriers at

the cell surfaces. This was accomplished in part for the earlier high resistivity cells by the development of the back-surface-field (BSF) layer. As has been pointed out, however, achieving higher efficiency appears to require the use of more heavily doped, low resistivity material where the BSF layer, as it is presently understood, is not effective.

A partial answer to this dilemma has been the development of the MINP and MINMIS cells, under partial NASA sponsorship, by Martin Green and co-workers (refs. 3 and 4). They have developed a technique for successfully passivating low resistivity n-type silicon surfaces without the use of a BSF layer. The technique involves careful deposition of several oxide layers on specially prepared silicon surfaces, and resulted in an AMO efficiency of 16.6 percent. The same group has recently made additional improvements in cell performance. The use of a v-grooved geometry on the cell front surface, e.g., has improved current generation and collection. Measurements made on such cells at NASA Lewis achieved 18 percent at AMO for the first time ever in a silicon solar cell. Even with these important gains the silicon cell is far from optimized. An additional significant improvement will result from a reduction of minority carrier recombination at the rear p-type surface typical of space cells, not only in terms of higher efficiency, but also in terms of increased radiation resistance. It also seems evident that the use of a dot grating geometry for the p-n junction, which has been successfully demonstrated in high resistivity cells (ref. 5), would be more effective if applied to the low resistivity cell (ref. 6).

#### GALLIUM ARSENIDE CELLS

Emphasis in the NASA solar cell research program during the past few years has largely shifted from silicon to the wide variety of semiconducting compounds formed from the elements in columns III and V in the periodic table. GaAs solar cells are a major concern at present, though as will be shown later, we have a growing interest in indium phosphide solar cells for space applications which may dominate our efforts. Figure 4 is a plot of efficiency versus band-gap for several solar cell materials in the AMO spectrum (ref. 7). The reason for interest in GaAs is clear: it has the potential for much higher efficiency than silicon. What is not evident from that figure, however, is the additional fact that GaAs is also more radiation resistant than silicon, at least in ground-based radiation testing. (It is not yet possible to make a full on-orbit comparison of the behavior of GaAs compared to silicon because there is insufficient actual flight data available.) Use of GaAs cells in space may be in either planar or concentrator arrays. The major interest in the NASA program has been on the development of a GaAs concentrator cell for use at modest (20x to 125x) concentrations. It is possible to operate a GaAs concentrator array in space at such levels with only passive, radiative cooling of the cells because GaAs cells can be operated at higher temperatures than silicon and still have higher efficiencies. The design goal has been to demonstrate cells with greater than 20 percent efficiency at 100 suns and an operating temperature of 80 °C. Under these conditions GaAs cells will have over twice the efficiency of silicon cells. Figure 5 shows two types of concentrator elements that are under consideration. The lower part of the figure shows a small (approximately 3 cm wide) semi-parabolic linear trough system (SLATS) (ref. 8) element which can be of variable length and can have a concentration ratio between 20x and 50x. It requires a cell string with an illuminated area 6 mm wide by the same variable length as the element. The other element is a

miniature Cassegrainian concentrator (MC2) (ref. 9) and will require a cell with an illuminated area only 4 mm in diameter. The small area of the cell is an important feature of the entire approach because it will lead to significant cost reductions compared to the use of planar GaAs cells, primarily because of the reduction in processed semiconductor area for a concentrator array. An additional assumption, of course, is that the cost per unit area of the concentrator optics will be significantly lower than the cost of the equivalent area of the processed semiconductor material. The anticipated cell output at the MC2 operating conditions is approximately 0.4 W. Efficiencies have been achieved in laboratory MC2 cells as high as 21 percent (ref. 10).

Cost is not the only reason for interest in concentrator arrays in space applications. A second very important reason is the inherent shielding provided by the concentrator element against the natural radiation environment encountered in many orbits. Although not as important for LEO orbits, the design may make possible the use of photovoltaic power generators in some of the mid-altitude orbits that have previously been dismissed because of the high density of trapped radiation encountered there. Beyond that, if high efficiency can be coupled with lightweight, low cost concentrator optics, such arrays could be flown on GEO and interplanetary missions as well.

There is general acceptance in the space solar cell community that the efficiency of planar GaAs cells ultimately should be between 22 percent and 23 percent at 1 sun AMO. A recent analysis by Weizer, et al (ref. 11), has shown that with proper attention to surface passivation and incorporation of a dot junction geometry in high resistivity GaAs material, efficiencies approaching 26 percent at 1 sun AMO should be possible. Any performance gains with such a structure will depend critically on achieving long minority carrier diffusion lengths in p-type GaAs, and on major reductions in the number of minority carrier traps at the surfaces and interfaces of the cell. The radiation resistance of this, or any, dot junction geometry solar cell will remain an open question when used in a conventional manner (i.e., as a planar cell with a glass cover over it for protection). The design may be particularly suited for concentrator applications, however, and should operate with even higher efficiencies than just mentioned. Values approaching 28 percent at 100x may not be out of the question.

#### INDIUM PHOSPHIDE SOLAR CELLS

Interest in InP as a space solar cell material has grown dramatically over the past few years. Figure 6 indicates the primary reason: InP solar cells may be inherently more radiation resistant than both silicon and GaAs cells. The plot is based on a compilation of preliminary data on such radiation resistance obtained from exposure of the cell types to 1 MeV electrons and to protons of various energies in laboratory tests. The superiority of the InP cells is evident, even at this very early stage of their development. Present theory indicates that the InP cells should ultimately achieve efficiencies over 20 percent at AMO. If they continue to show their present level of radiation tolerance as efficiencies improve (currently approximately 14 percent AMO), they will surpass silicon cells altogether, and will have higher EOL outputs than GaAs cells in GEO and other radiation-intensive environments. Figure 7 summarizes the current situation. InP space cells have been under development for about 5 years. Yet they are already better than the usual production-quality silicon cell, which is typically less than 14 percent efficient.

In addition to their apparent hardness to space radiation, InP cells also appear to be annealable at relatively low temperatures. Figure 8 shows that complete recovery of output is possible with InP after heating the cell to 125 °C for 10 min (ref. 12) even when cell output has essentially been destroyed by 1 MEV electron irradiation. Neither silicon nor GaAs exhibit such startling behavior. There is not as yet any understanding, on a microscopic scale, of the reasons for such behavior in InP. Even more startling is the behavior shown in Figure 9 (ref. 13). Simply exposing InP cells to sunlight while irradiating them with 1 MEV electrons anneals a significant fraction of the power they would lose if irradiated in the dark. Such an effect is absent altogether in silicon and GaAs at less than 1 sun levels and ambient temperatures. (It is known that self-heating of GaAs cells under concentration to temperatures approaching 200 °C will cause some annealing, but the effect is essentially thermally induced.) A great deal of work remains to be done to understand and exploit these phenomena, but the potential payoff for enhanced space solar array performance is very promising.

### SUPERLATTICE SOLAR CELLS

The final area of research to be discussed here concerns a solar cell design based on a new class of electronic materials known as superlattices. Without going into details, superlattice materials are essentially comprised of very thin layers (typically 50 to 350 Å) of different semiconductor materials that have similar crystallographic properties, but different electronic properties; in particular, they have different semiconducting bandgaps. A typical example is an alternating layer structure of GaAs and AlGaAs. There are several reviews of these materials available in the general literature (ref. 14). A variation of the usual compositional superlattice can be found in the so-called GaAs nipi structure, which is simply a continuously grown single crystal of GaAs with alternating thin regions of n and p dopants, separated by narrow intrinsic, or undoped regions. The net effect is a modification of the bandgap of the material into an effective bandgap that can be tailored within limits to have a range of values that will vary depending on the dopant concentrations. More importantly, the material behaves as though the direct bandgap of GaAs has been replaced by a real-space indirect bandgap between the electron states in the conduction band and the hole states in the valence band. As a result, photogenerated holes and electrons will be spatially separated within picoseconds of their creation, and will have almost no chance to recombine over lifetimes several times longer than they exhibit in ordinary single crystal material. Bulk recombination losses could seemingly be almost eliminated in such a material, and extremely high collection probabilities attained. Figure 10 shows a schematic representation of the new band structure of a nipi superlattice, and Figure 11 illustrates a schematic cross section of a proposed nipi solar cell. Of particular interest for space applications is their behavior when exposed to space radiation. Preliminary computer calculations (ref. 15) of the performance of these devices indicates that they should not only show efficiency enhancement, but that the extremely long minority carrier lifetime should give them superior resistance to radiation damage. Research in this important area has hardly begun, but again, the promise is significant.

## CONCLUDING REMARKS

The intent of the preceding discussion has been to give a brief overview of the scope of the NASA space solar cell research and development program. It has by no means been an exhaustive survey of even the cell research itself, let alone the wide range of programs in array technology and development. A hallmark of all areas of the space photovoltaic program, however, has been to emphasize the achievement of high efficiency and performance. Experience has shown it to be ill advised to attempt to compromise on cell quality to achieve lower cell costs. A primary reason is that cell performance has such leverage on the balance-of-system (BOS) costs that the approach historically has not paid off. The same may well prove to be true for terrestrial applications, particularly when consideration is given to the reliable generation of large amounts of power, though the terrestrial program has emphasized the latter approach (i.e., search for a compromise from the very first) rather heavily. Where NASA and terrestrial interests in high performance have overlapped there has been good synergism, and although it has been usual to expect that space technology provides the spin-offs, that is not always the case. The dot junction cell structure is a good illustration. The first successful demonstration of that geometry has been in silicon cells operating under concentration ratios up to 700x at AM1.5 (ref. 16) - i.e., designed for terrestrial application. In this case the demonstration of high performance first, without compromising it for presumed cost considerations, is consistent with the historical practices in space solar cell research. It is hoped that pertinent aspects of the space cell research described in this paper could be of benefit to terrestrial applications where a similar research and development philosophy exists.

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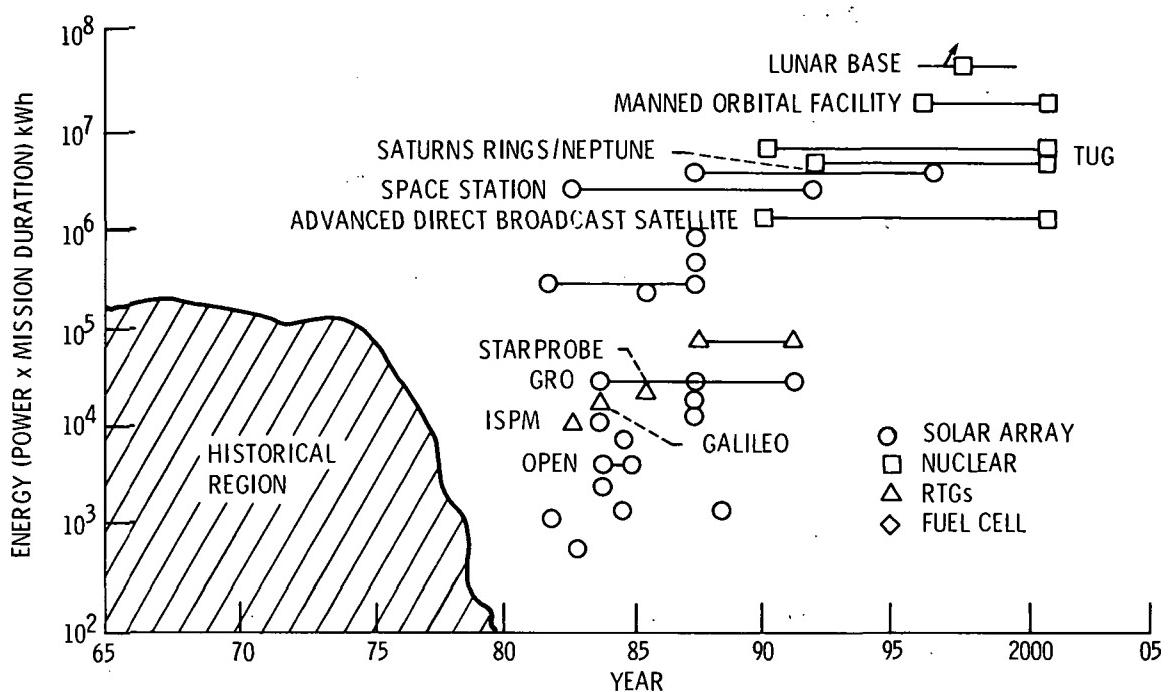


Figure 1. - Future space energy demands.

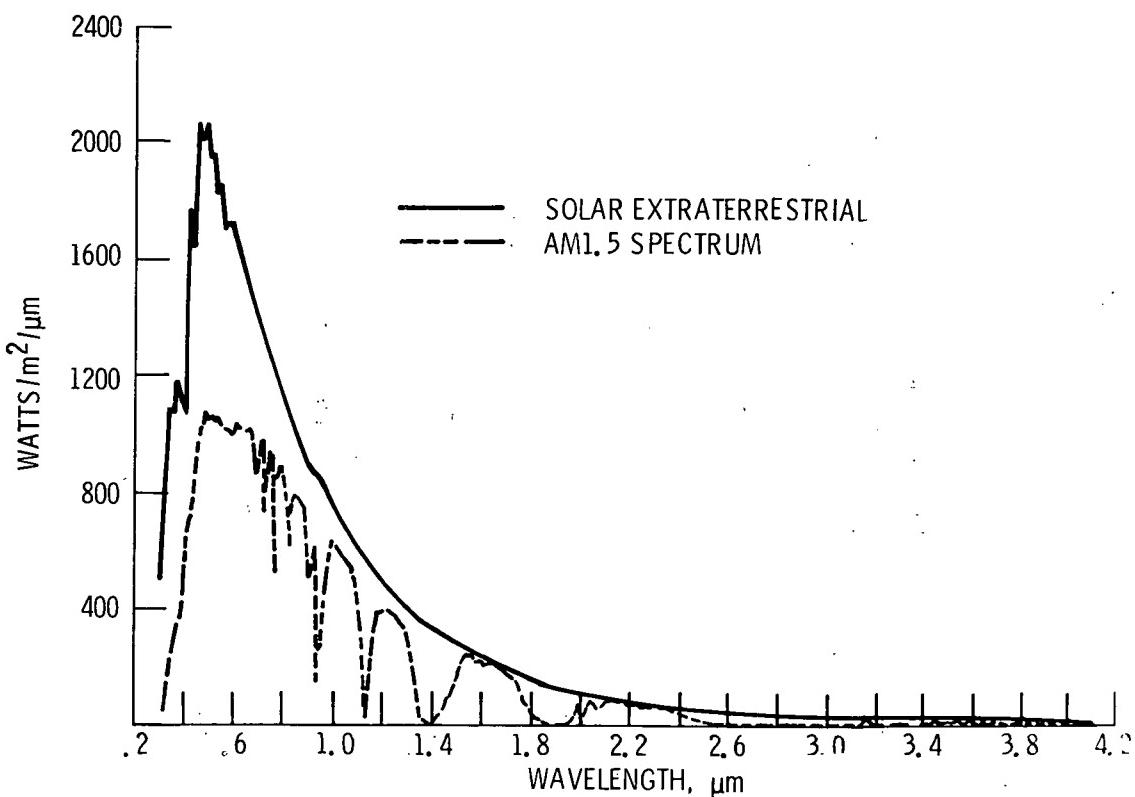
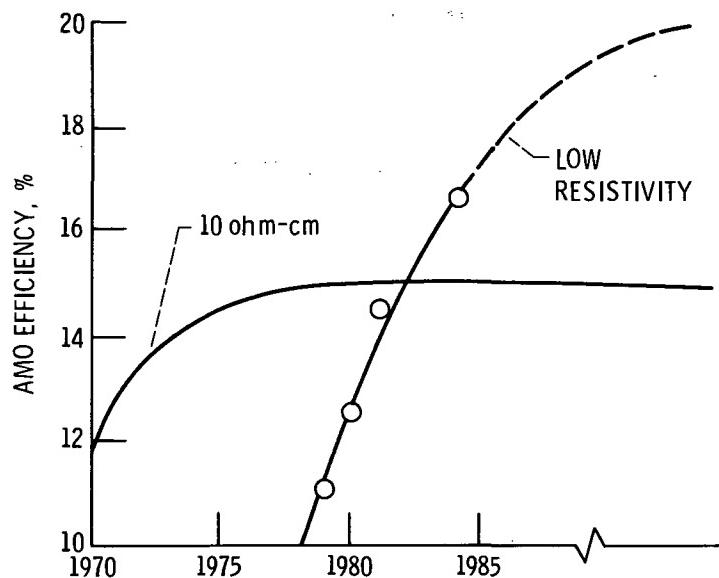


Figure 2. - Solar spectral irradiance.



- CONVENTIONAL 10 ohm-cm CELL FULLY OPTIMIZED
- LOW RESISTIVITY CELL DEVELOPING RAPIDLY
- 20 % EFFICIENCY NEAR TERM POSSIBILITY

Figure 3. - Developmental history of the silicon solar cell.

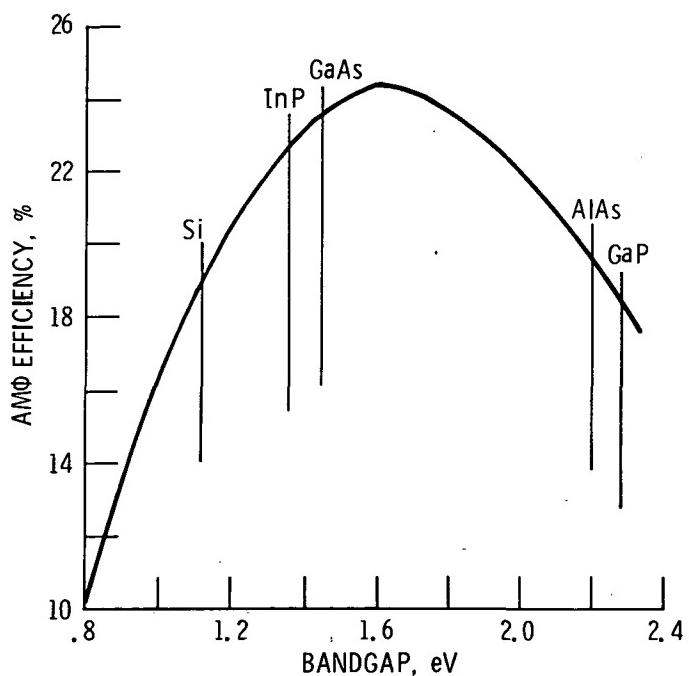
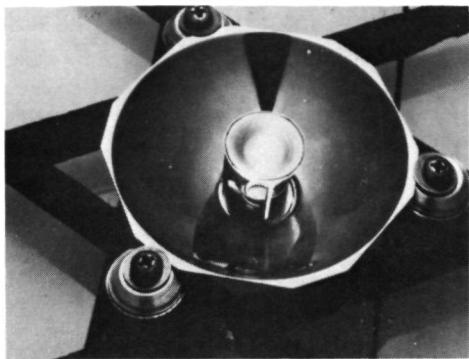
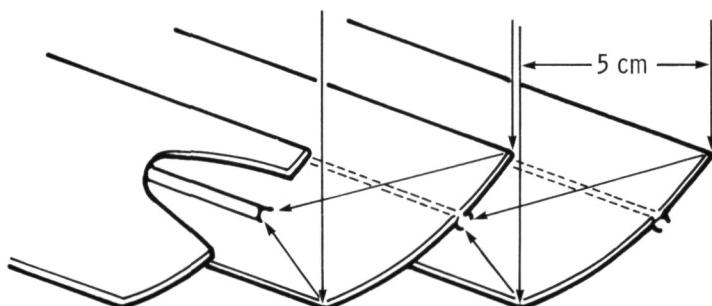


Figure 4. - Efficiency versus bandgap in AMO.

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COLOR PHOTOGRAPH



MINIATURE CASSEGRAINIAN CONCENTRATOR ELEMENT



SCHEMATIC OF SEMI-PARABOLIC LINEAR APERTURE TROUGH SYSTEM (SLATS)

Figure 5. - Mini-cassegrainian and SLATS elements.

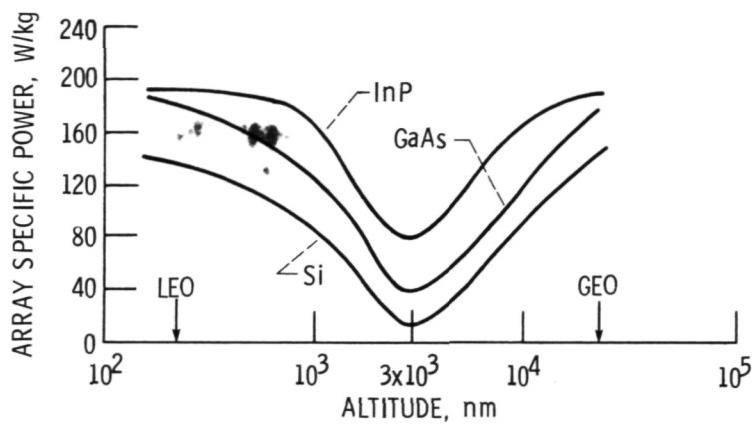


Figure 6. - Comparison of solar array calculated output as a function of orbit altitude, based on 1 MeV electron equivalent fluences. Time in orbit = 7 years, circular orbit,  $30^\circ$  inclination,  $T = 60^\circ\text{C}$ .

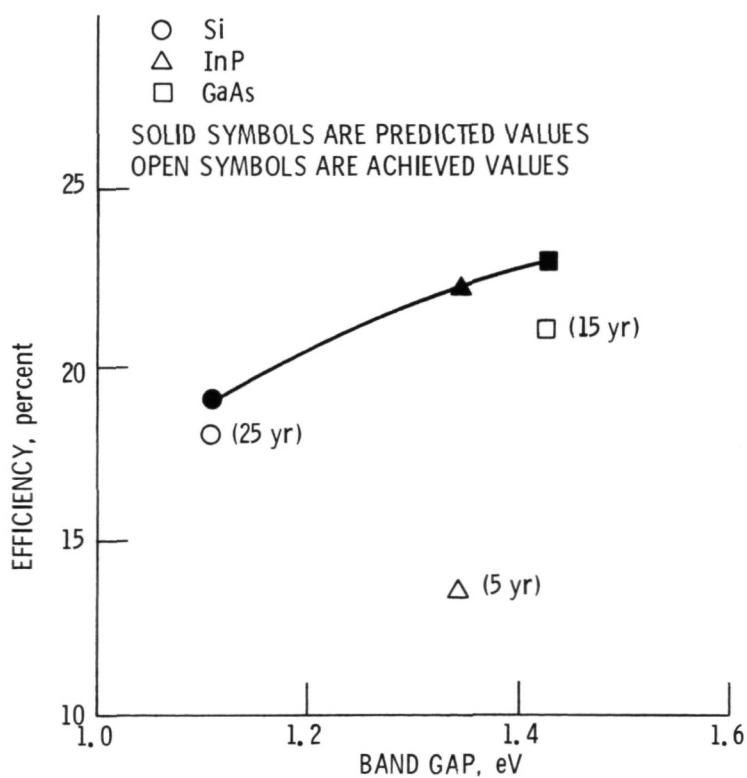


Figure 7. - Predicted and achieved AMO efficiencies.

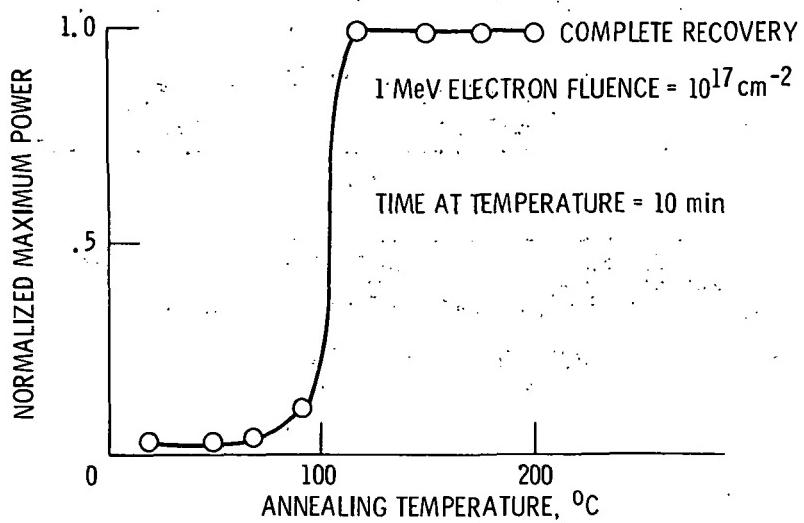


Figure 8. - Radiation damage removal in InP by low temperature heating.

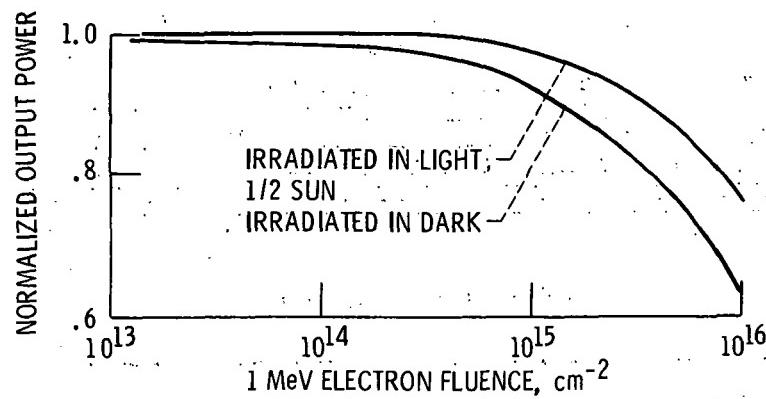


Figure 9. - Radiation damage removal in InP by incident light.

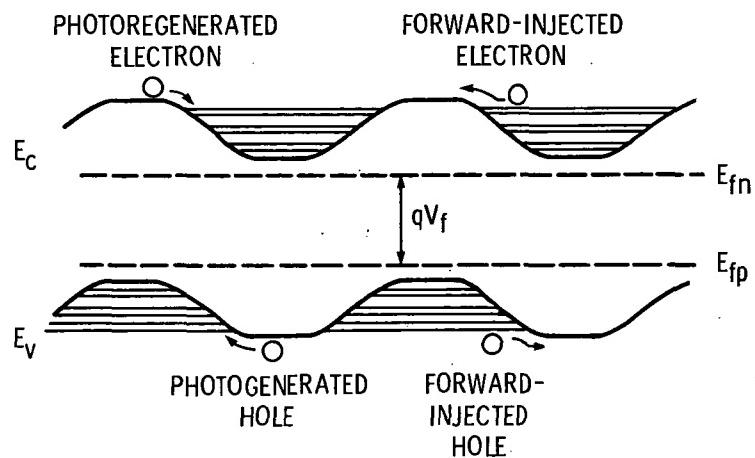


Figure 10. - Band diagram of radiation hard superlattice cell under illumination.

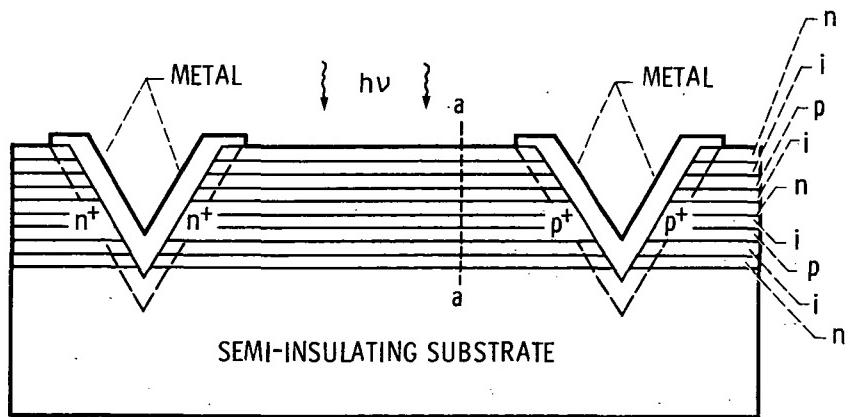


Figure 11. - Cross-section of proposed radiation hard superlattice solar cell.

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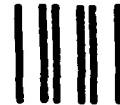
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